PULSED NEUTRON SOURCE ON A BASE OF LEU TARGET FOR THE MOSCOW MESON FACTORY

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INTRODUCTION

The pulsed neutron source based on the high-current proton linac (proton energy 600MeV, average current 0.5-1.0 mA, pulse width 100-200 μs and repetition rate up to 100 Hz) and proton storage ring (pulse width 0.32 μs, average current up to 0.4 mA, repetition .rate 100 Hz) /I/ that is under construction at INR RAS will allow one to develop a wide range of research on condensed matter and nuclear physics with thermal and epithermal neutrons.

The neutron source consists of the following principal parts (see Fig.1):

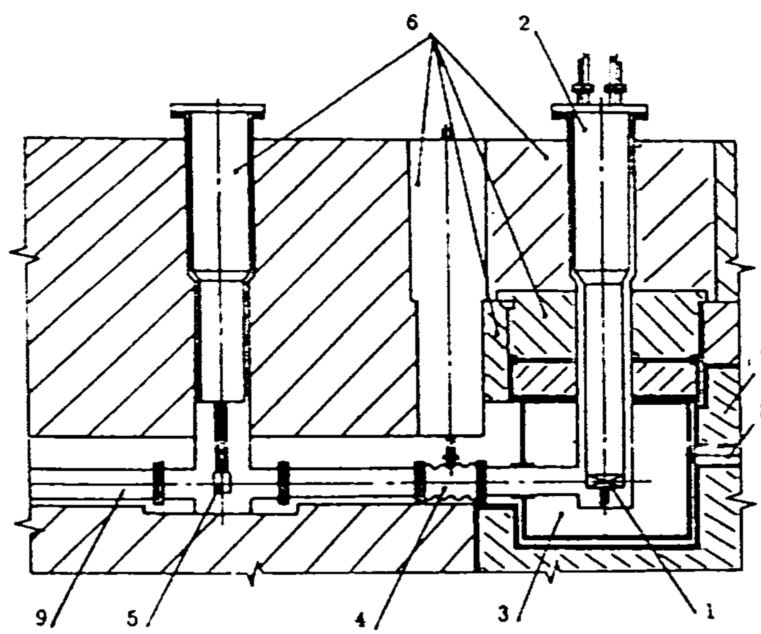

Fig.l. Pulsed neutron source layout:
I - core; 2 - target vessel with steel shielding plugs; 3 - gas tank;
4 - remote controlled vacuum seal; 5 - proton beam monitoring system; 6 - shielding plugs;
7 - thermal shielding; 8 - neutron guides in biological shielding; 9 - proton guide.

- water cooled vessel containing target, moderator, reflector and top steel shielding with coolant pipes inside;
- gas vessel with vacuum bend reducing scattered neutron backgrounds at the lower moderator and joining the target and ion guide vacuum system (though another design suppressing neutron background may be used);
- remote-controlled vacuum seal which provides disassembly of the whole neutron source;
- proton beam monitoring system.

The scheme allows us to use vessels with different targets and moderators (including cryogenic ones) and to replace all equipment in the central part, as well as to modify the source. A set of Ti-coated tungsten plates or tight lattice of natural uranium rods in stainless steel cans placed in Al-alloy vessel and cooled with light water now uses as neutron target.

In future we planned to use enriched uranium targets with multiplication up to 10 without significant changes of the existing target design /2, 3/. Using the multiplying target will allow us:

- to increase by several times the intensity of the pulse neutron source at repetition rates from 10 to 50 Hz, which is the most suitable range for time-of-flight experiments;
- to decrease the beam current usage down to 5-50% of the total accelerator intensity, thus allowing more experimental programs to be executed concurrently;
- to use a relatively low proton current in the storage ring (< 0.5 mA); this will make easier the achievement of required operational parameters and will increase its stability;
- to provide a high performance neutron source at the initial stage of accelerator operation, before the design parameters are achieved.

The design of the multiplying target on a base of HEU (90%) was made early and now we carry out the LEU target's design to provide the full-scale testing.

The LEU target design is close to the classical wing arrangement. Thus, if a powerful proton beam is used, it allows us:

- to minimize in a most easy and rational way the inevitably negative influence of several layers of material between the target and moderators, the inlet and outlet collectors, fuel element lattice, etc.;
- to provide reliable cooling of the proton beam window;
- to ensure nuclear safety of multiplying target and to use highly enriched uranium only in minimal quantity.

PRINCIPAL SCHEME OF LEU TARGET

The part of the neutron source with HEU multiplying target shown in Fig.2 includes the core, the lower and upper moderators, and the Be-reflector surrounding the upper moderator.

The deficiencies of HEU scheme is following:

- fuel elements with uranium alloy are under the direct action of intensive proton beam. From the point of view of the experience under uranium targets at the Ernest Rutherford laboratory (England) the mean time to failure of such targets was about 3 months. At the same time the mean time to failure of tantalum targets was some years,
- big amount of using of high enriched uranium (~25 kg).

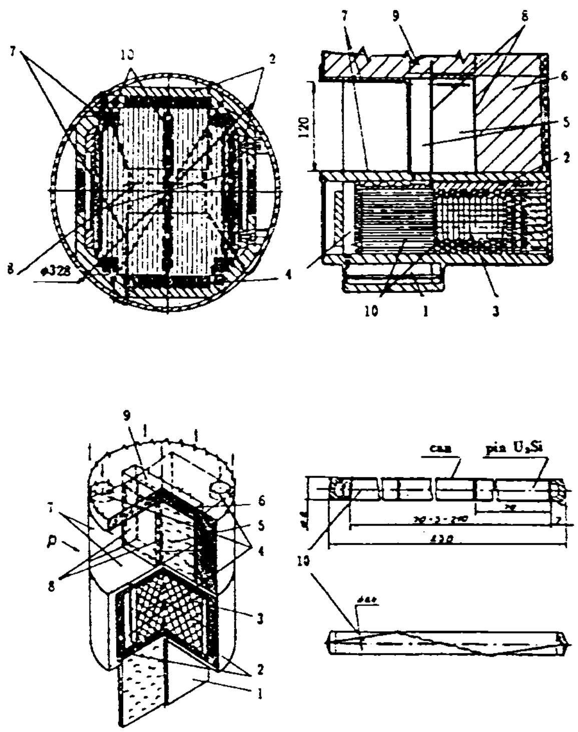

Fig.2. Central part of the pulsed neutron source
I - lower moderator; 2 - Ti-Gd decoupler; 3 - core; 4 - coolant inlet and outlet;
5 - upper moderator; 6 - Be-reflector; 7 - Gd - decoupler; 8 - Ti-Gd - insertion;
9 - Be-plug; 10 - fuel element

That is a reason why we decided to move out the fuel elements with enriched uranium from the direct action of intensive proton beam and to dispose them around the compact titanium target. But that decreases the conversion coefficient (output of neutrons per one proton) in 1.35 - 1.4 times. For compensation of this effect we need to increase the multiplication in same times.

Moreover, the geometric factor of the whole facility will be degrading. Those two conditions (central tungsten insert and increasing the multiplication coefficient) give us increasing of the volume of using high-enriched uranium in 2.5-3 times.

For escape of that negative effect and for decreasing the amount of highly enriched uranium we developed the dual-chamber core /see Fig.3/.

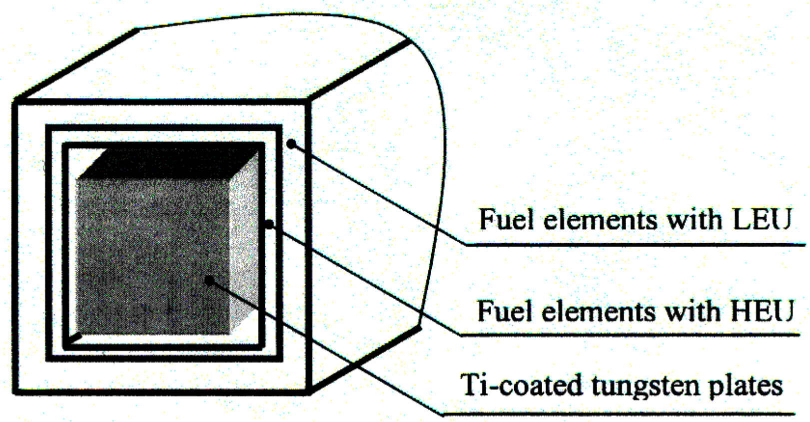

Fig.3. Principal scheme of LEU target

In our new design the core with low enriched uranium dispose after the highly enriched core. Water moderators have light yield to channels and are in the low enriched core. Both cores (HEU and LEU) connected by fast and intermediate neutrons. Decoupler is between these zones. For prevention of pulse duration long time the moderators were separated from zone of LEU by the decoupler.

TUNGSTEN AND URANIUM ELEMENTS

The tungsten target contains 25 plates made of W of high purity (99.95 wt.%) having dimensions of 5×7×160, 5×57×220, 10×57×160 and 10×57×220 mm. The design provides a 0.7 mm gap between the plates for coolant flow. The tungsten plates have a titanium corrosion resistant coating 10 μm thick. Without protection the rate of tungsten corrosion under operating temperature conditions may as great as 50 microns per year /4/.

The uranium target consists of cylindrical fuel elements with intermetallic substoichio-metric composition in the form of U_3Si in stainless steel cans of 8 mm diameter and 0.3 mm wall thickness. The fuel element design was chosen for the following reasons:

- due to the high price of highly enriched uranium, it is important to provide that the lifetime of the target be at least 3-5 years, corresponding to fuel burnup 1-2 at.%;

- during operation, the target will experience regular and irregular thermal shocks. These negative phenomena are almost eliminated if the fuel is arranged in the target in the form of cylindrical rods /5, 6/.

The triangular packing of the fuel rods, 8-9 mm diameter with a gap between them about 0.4 mm, makes possible single-phase water cooling of the target at a water pressure $(1.5\text{-}2.0)\times10^5$ Pa and flow rate of 3.5-4.5 m/s.

In this case the volume fraction of the coolant does not exceed 20%, moreover it provides acceptable physical characteristics of the neutron source and allows removal of the heat power up to 2.0-2.5 MW at proton pulse repetition rates up to 50 pps /7-9/.

The choice of a high density uranium alloy for fuel core was made taking into account the properties, manufacturing technology and existing experience with their operation under conditions similar to those of neutron target. We observed /Table 1/ the characteristics of two types of alloys: 1 - alloys based on stable phases of the type of U_3Si /10/ and 2 - alloys based on metastable solid solutions of the type of U-Mo and U-Nb-Zr /11,12/, both showing satisfactory resistance to corrosion in water up to 200°C.

Table 1. Characteristics of alloys

Alloy (fractions expressed as weight percents)	U-3.8% Si[1]	U-2.9% Si[1]	U-6% Mo	U-9% Mo	U-5%Nb-5%Zr
Density, g/cm^3	15.1	16.1	18.3	18.1	16.1
Uranium content, g/cm^3	14.5	15.8	17.1	16.5	15.1
Max allowable temperature, °C	550[2]	550[2]	350	350	400
Corrosion rate in water, mg/cm^2hr:					
at 100°C	0.01	0.02	0.01	0.01	0.01
at 200°C	0.11	0.07	0.03	0.01	0.04
at 200-350°C (after annealing at 350°C)	0.5	0.5	1-2	0.5-1	>5
Thermal conductivity at 200°C, W/m·K	19	21	23	21	22

1 Contains 0.2-0.4 % of elements stabilizing properties of U_3Si.
2 Recommended temperature, tested up to 680°C.

The maximum operating temperature of U-Mo and U-Nb-Zr alloys depends on the thermal stability of their corrosion resistant metastable γ-phases. After several hours at 350°C the beginning of γ-phase disintegration with the appearance on grain boundaries of an α-phase subject to corrosion was detected. This results in the loss of the desired fuel core mechanical properties and an increase of the corrosion rate by 10-100 times, up to unacceptable values 0.2-1.0 mg/cm^{2}hr. In several cases the catastrophic destruction of U-Mo samples after 10-30 days of exposure in water was observed. Under conditions of frequent changes of the operation regime, shut-downs, uneven heating (thermal shocks ~10·15°C it is impossible to provide reliable thermal contact between the can and fuel rod based on U-9% Mo. Experience with U-Mo alloys in breeder blankets with burnup ≤1% shows that the thermal contact is not always achieved even in the case of rare changes of operating conditions and shut-downs.

On this reason for the proton beam of the Moscow meson facility, U-9% Mo alloy can be used for the targets with low multiplication coefficients ~3-5 at pulse repetition rates ~25-50 pps, respectively. At larger multiplication coefficients, the temperature of both central and peripheral fuel elements exceeds the temperature of γ-phase stability.

For fuel based on uranium silicides, the temperature of the outer layers of fuel elements is about 130°-140°C even at multiplication coefficients 8 - 10. The operating temperatures and corresponding rates of corrosion for U-9% Mo and U-2.9% Si differ substantially.

Swelling of uranium alloys under irradiation at temperatures less than 350-400°C is caused by accumulation of fission products in the crystalline lattice with the rate of 2-3 vol.% per 1 at.% of burnup. For fuel elements made of U_3Si the diameter increase of fuel element will be 0.1-0.3 mm at a burnup of about 2 at.% (Fig.4).

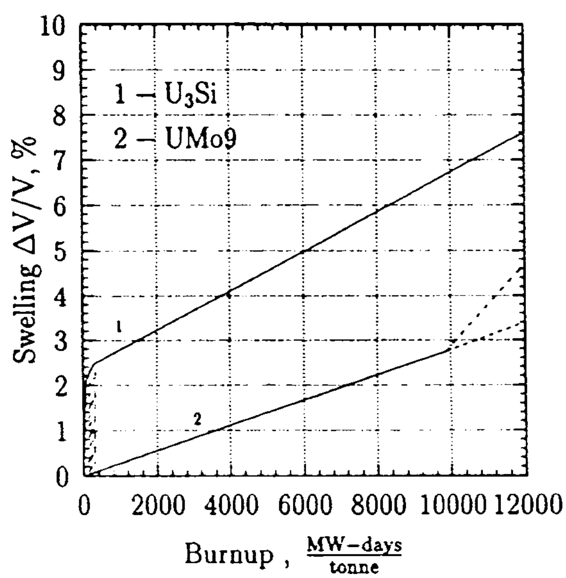

Fig 4. Swelling of meat’s materials

For comparison, on the same figure, the swelling of U-9 wt.% Mo alloy is presented. For both cases the swelling is shown not accounting for the restriction factor of the cladding.

Radiation amorphization of uranium silicide at temperatures below 210°C and burnup more than 10^{-4} at.% is a useful phenomenon /20/, since it provides:

- increased corrosion resistance of fuel;
- full thermal contact between core and can after several hours of operation; according to experimental investigation, this contact was not broken under non-stable temperature conditions;
- decreased negative influence on fuel element lifetime due to non-uniform core swelling and deformation under thermal shocks.

As we have established, uranium silicide in the amorphous state exhibits radiation creep comparable to that of the crystalline state under temperatures a little lower than the melting point. According to our calculations there will be an outer layer of fuel in the amorphous state under the full range of operating conditions of the target. This outer amorphous layer, as we expect, will prevent the core from cracking, unlike the case of U-Mo and U-Zr-Nb alloys.

At the most powerful operation conditions (the case of a multiplying target) the local maximum heating per pulse will be ~15°C. In order to decrease the additional influence of thermal shocks the fuel core is split into three parts (Fig.2) /5/. The meats made of substoichiometric silicide U - 2.9 wt.% Si are cladded in stainless steel without a barrier sublayer, since at temperature less than 500°C and exposure for one year, the interaction layer does not exceed 10 microns.

Prototypes of fuel elements were tested under reactor conditions with water cooling for 3.5 years to a burnup of 3 at.%. The maximum local power density of the silicide core ranged up to 660 W/cm^3. This power density for a multiplying target at a design beam current of 0.5 mA will be achieved at a frequency of 25-30 Hz. Increasing the repetition rate up to 50 Hz will raise the power by two times and fuel core temperatures will be close to their operating limit. Thus the parameters of target operation demand careful investigation.

Experience in developing, testing and using the uranium silicide as a high-density fuel for light-water reactors is an additional reason for choosing it.

Besides the silicide, other high density amorphyzing compounds of U_6Me - type, where Me is Ni, Co, Fe, Mn and their combinations were investigated. But their corrosion resistance in water under temperatures about 200°C was insufficient. Taking this into account as well as the level of investigation of uranium silicide, that material was finally chosen as a fuel for target elements.

The arrangement of fuel elements in the target lattice and their separation is provided by stainless steel wire 0.4 mm in diameter. Thermal - hydraulic calculations of the compact fuel element lattice was carried out on the basis of experimental data summarized in /7, 8/.

In order to compensate for thermal expansion and the swelling of fuel elements in the transverse direction and to prevent vibration due to coolant flow, springy elements embracing the core from three sides are used. The most suitable materials for springy elements is Zr-Mo alloy since it retains elasticity under reactor conditions and has good compatibility with other target materials.

CONCLUSION

1. The neutron source with HEU multiplying target has deficiencies.
2. Using the new design of neutron source with HEU and LEU we suppose:
   - considerably increase the mean time to failure,
   - considerably decrease the amount of using HEU (2-2.5 times),
   - improve the geometric factor,
   - increase the area of moderators that have a light yield to neutron channels and correspondingly increase the numbers of channels and thus increase the efficiency of the whole facility.
3. For HEU and LEU zones fuel elements on a base ofU_3Si was chosen.

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